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Material Balance and Energy Balance Analysis for Syngas Generation by a Pilot-Plant Scale Downdraft Gasifier

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Biomass derived synthesis gas (Bio-syngas) was produced by a pilot-plant scale downdraft gasifier, using oak tree wood chips as the raw material and air as the oxidation gas. The conditions and parameters for a stable gasification process were explored. The material balance and energy balance of this pilot-plant-scale gasification were studied. The temperatures in the combustion and reduction zones of the gasifier were stabilized between 700–900 °C. The flow rate of the producer gas was 65 Nm^3/h. The consumption rate of wood chips was 26–30 kg/h. The syngas yield was 2.2–2.5 Nm^3/ kg wood. The producer gas was composed of about 48% N_2, 21% CO, 18% H_2, 10% CO_2, and 2% CH_4. The carbon conversion rate was above 92% (from wood to CO, CO_2 and CH_4) and the hydrogen conversion rate was 67–76% (from wood to H_2 and CH_4). The LHV (lower heating value) of the producer gas was 5.1–5.5 MJ/Nm^3. The energy conversion rate was about 59–65% (from wood to the producer gas) and the waste heat energy in the producer gas was 10–12% of the wood heating value.

Keywords: Gasification, Downdraft, Material Balance, Energy Balance, Wood, Syngas, Producer Gas.

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1. INTRODUCTION

The resources of fossil fuels are diminishing while global energy demand is soaring. Therefore, replacement or partial replacement of fossil fuels by renewable energy is necessary for sustainable development of human society. Renewable energy includes wind energy, solar energy, bioenergy, and so on.[1] Compared to wind energy and solar energy whose production is greatly restricted by location and climate, bioenergy production is relatively practical with abundant availability of feedstocks. Bioenergy is basically obtained by converting organic materials, such as lignocellulosic biomass, algae, and food processing waste, into applicable energy carriers, such as hydrocarbons, biogas, and alcohols.[2–4] Bioenergy has carbon neutral or carbon negative property in its production-application life cycle as it greatly reduces green house gas emission compared to fossil fuels.[5–7]

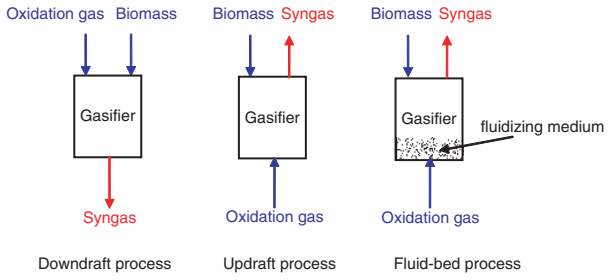
The first generation biofuels are mainly produced from crop-based biomass. For example, ethanol is largely produced from corn and biodiesel produced from oil crop.[8,9] The major disadvantage of crop-based biofuels is to impose pressure on arable land as well as food and feed supplies. Lignocellulosic biomass, such as agricultural residues and forestry waste, is promising feedstocks for new generation biofuels due to their domestic and abundant availability. Two main options to convert lignocellulosic biomass to high-value fuel products are biochemical processes and thermochemical processes.[10–12] Thermochemical processes mainly include gasification, liquefaction, and pyrolysis technologies.[11–29]

Gasification has been traditionally applied to produce gaseous and liquid energy products from coal.[14,15] Biomass gasification is currently attracting more and more attention due to renewable energy demand.[13,14,16–29] Scheme 1 demonstrates three major gasification processes. Downdraft and updraft gasification systems belong to fixed-bed gasification processes. The oxidation gas flows downward in the downdraft gasifier while upward for updraft gasifiers.[13,16] Updraft and fluid-bed gasification processes have higher heat-transfer efficiency than downdraft process, but they produce much more tar and impurities in the syngas. Downdraft gasifier, therefore, has a higher yield of the producer gas than the other two processes.[13,16] Moreover, the downdraft process is simpler and easier to control; therefore, downdraft gasifier is most prevailing in the U.S. market.[13]

There are many reports on downdraft biomass gasification systems,[17–25] but detailed mass and energy analysis

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Scheme 1. Schematic illustration of major gasification processes.

data are not widely available,[17–20] especially for large scale gasifiers. In this study, a pilot-plant scale and highly automatic downdraft gasification system was investigated and evaluated. The energy balance and mass balance for woody biomass gasification were analyzed. This study provided some insights and guidance for modification and improvement on gasification technology.

2. EXPERIMENTAL DETAILS

2.1. Equipment and Materials

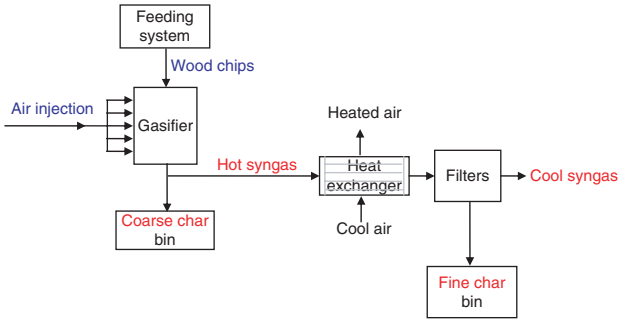
Oak-tree wood chips (1/2–2 in.) were used as raw materials for the gasification process. Their moisture content was analyzed with an OHAUS MB200 balance (Certified Scale, Inc., Menomonee Falls, WI). The sample weight was measured at room temperature and then heated to 160 °C and held at that temperature until it reached a constant value (changes < 0.01 g in 60 s). The percent of weight loss was regarded as the moisture content. Wood chips with the moisture contents of 8.3% and 9.5% were used in this study for material balance and energy balance analysis.

The elemental composition of wood chips and biochars was analyzed with a CE-40 Elemental Analyzer (EAI Exeter Analytical, Inc., Chelmsford, MA). At least three measurements were conducted for each sample and an average value was taken for calculation of mass balance and energy balance. The results are listed in Table I.

The syngas composition was analyzed using an Agilent 6890N GC (Santa Clara, CA) equipped with a Carboxen 1010 PLOT column and TCD detector. Argon was used as the carrier gas. The processing temperatures were obtained from the host computer, which acquired the data from installed thermocouples. The volume concentrations of the main syngas components were monitored online by

Table I. Elemental analysis results of wood chips and biochars (wt%).

Sample	Carbon (%)	Hydrogen (%)	Nitrogen (%)	Remaining (%)
Wood chips	44.70 ± 0.40	5.90 ± 0.10	0.40 ± 0.10	49.00
Coarse char from the gasifier	47.20 ± 2.40	0.90 ± 0.10	0.40 ± 0.03	51.50
Fine char from the filter	32.40 ± 0.60	0.90 ± 0.02	0.30 ± 0.00	66.40



Scheme 2. BioMax 25 gasification system.[30]

a portable gas analyzer throughout the gasification process (7900P4C, NOVA Analytical Systems, Inc., Niagara Falls, NY).

2.2. Description of BioMax 25 Gasification System

The pilot-plant scale gasifier, BioMax 25, was purchased from Community Power Corporation (Littleton, CO). It was a highly automatic downdraft gasification system with a host computer to control the gasification process. As illustrated in Scheme 2, its main components included a feeding system, a gasifier, a heat exchanger and filters. There were multiple thermocouples and pressure transducers installed in the system to monitor the running of the gasification system and to provide input to the computer. The computer program would adjust the air injection rate and wood chip feeding rate according the setting point of the producer gas flow rate that was set at 65 Nm^3/h in this study.

The auger feeding system was installed with the gasifier and its motor would be activated when the fuel level in the gasifier fell below the setting point. The gasifier was designed with five levels of air injection loops with each loop having six injection ports to the gasifier (Fig. 1), which ensured air to be evenly distributed into the gasifier at the same level. The air injection rate was controlled by the computer program and varied according to the temperatures inside the gasifier. The heat exchanger cooled the producer gas from 500–700 °C to about 110 °C by ambient air. After cooling down, the producer gas first went through parallel bag filters to remove the fine particles and then filtered through activated carbon to remove the tars. The cool syngas was finally compressed into a storage tank or sent to a burner.

3. RESULTS AND DISCUSSION

3.1. Process Profile

A downdraft gasification system was illustrated in Figure 1, with each level corresponding to each step in the gasification process. The energy needed for reduction reactions and gasifier heating was provided by the combustion of

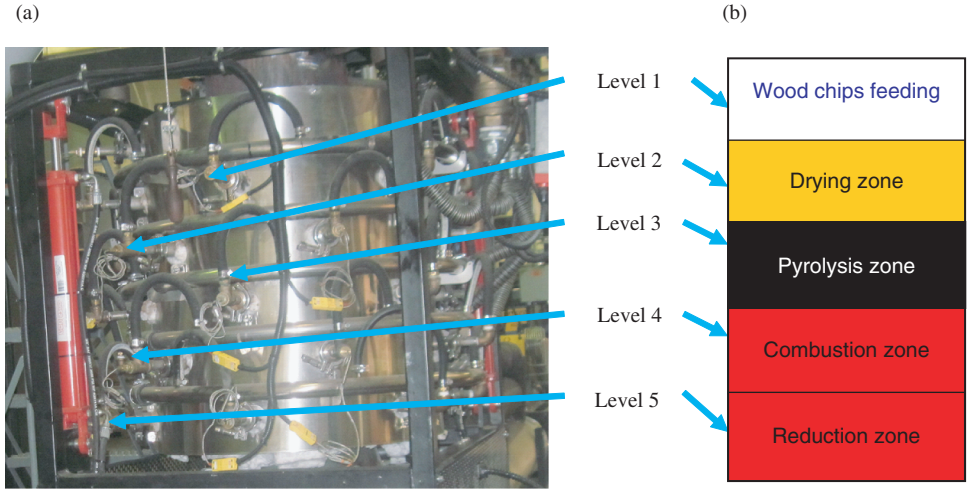


Fig. 1. Configurations and gasification process in the downdraft gasifier: (a) The air injection levels and temperature monitoring positions in the downdraft gasifier, and (b) Processes which occur inside the gasifier.[13, 30]

wood chips; therefore, no external heating was provided. The processing temperatures and pressures were monitored and controlled by the program (BioMax 25 version 1.28) in the host computer, which acquired the data input from the installed thermocouples and pressure transducers.

3.1.1. Temperature Profile

The oxidation gas (air) was injected through five injection loops as displayed in Figure 1(a) with temperatures being monitored at these five levels. Figure 2 show temperature profiles of two different gasification runs. As seen from Figures 2(a) and (b), both runs had a very similar temperature profile regardless of slight difference in moisture contents of wood chips and room temperatures. Also, for both runs, the temperatures of Levels 3–5 were stabilized between 700–900 °C. By contrast, Levels 1 and 2 fluctuated to some extent, which were most likely affected by wood chips feeding to the gasifier.

Figure 3 shows the temperature profiles of syngas getting into ($T_{\text{hex in}}$) and getting out ($T_{\text{hex out}}$) of the heat exchanger. When the gasification process run at a stable stage (from 60–300 min), the temperatures were very stable with $T_{\text{hex in}}$ and $T_{\text{hex out}}$ being kept at about 550 °C and 100 °C, respectively.

3.1.2. Gas Flow Rate

As shown in Figure 4, the actual gas flow rate during the gasification process was stabilized at the setting value of 65 Nm^3/h.

3.2. Material Balance and Energy Balance Analysis

3.2.1. Properties of Wood Chips and Biochars

Table I shows the elemental compositions of wood chips and biochars. The biochar collected directly from the gasifier (coarse char) had much larger sizes than that from the filters (fine char). The coarse char had higher carbon content than fine chars while two types of char had a similar hydrogen content and nitrogen content. The properties of biochars will be studied in detail in our future studies.

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3.2.2. Producer Gas Property

The volume concentrations of the main gas components in the producer gas (i.e., N_2, CO, H_2, and CO_2) were pretty stable during the gasification process (Fig. 5). As indicated in Table II, the producer gas was composed of about 48% N_2, 21% CO, 18% H_2, and 10% CO_2. In addition to the main gas components, the producer gas also contained some water vapor and trace amounts of other gases.

The LHV (lower heating value) of the producer gas (or syngas) was calculated by Eq. (1).[13] The calculated LHV of the producer gas was 5.1–5.5 MJ/Nm^3 (see Table III). The LHV of wood chips was 19.59 MJ/ Nm^3.[13]

$$LHV_{\text{syngas}} = 12.622P_{\text{CO}} + 10.788P_{\text{H}_2} + 35.814P_{\text{CH}_4} \quad (1)$$

3.2.3. Material Balance

The charcoal residues inside the gasifier were regarded the same after each gasification run. Before every run, the charcoal inside the gasifier was replenished with hardwood charcoal to the same level if there were some small changes. It was assumed that all the ashes and biochars produced during gasification were collected into the char bins. The ashes and tars that were trapped inside the gasification system were neglected when calculating the material balance and energy balance.

The flow rate of the producer gas was set at 65 Nm^3/h. The feeding rate of wood chips was also automatically

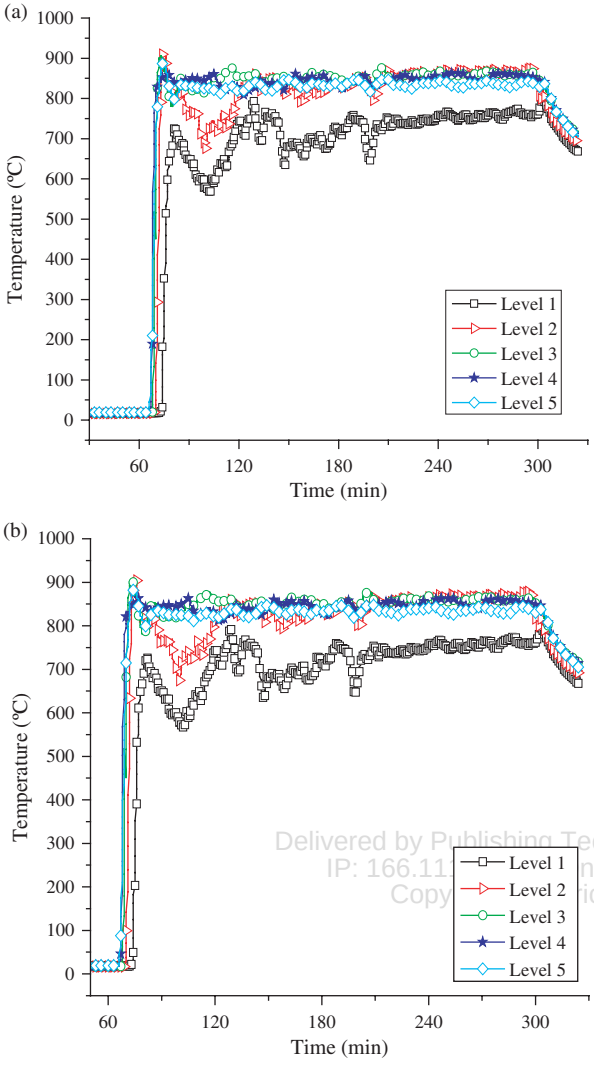


Fig. 2. Temperature profiles at different gasifier levels during three gasification runs: (a) wood chips with 8.3% moisture content and room-temperature air at ~20 °C, and (b) wood chips with 9.5% moisture content and room-temperature air at ~23 °C.

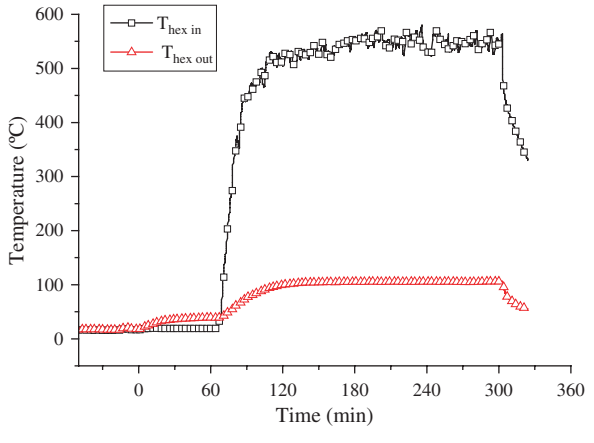


Fig. 3. Temperature profile of the producer gas when getting in and getting out of the heat exchanger during the gasification run (wood chips with 9.5% moisture content and room-temperature air at ~23 °C).

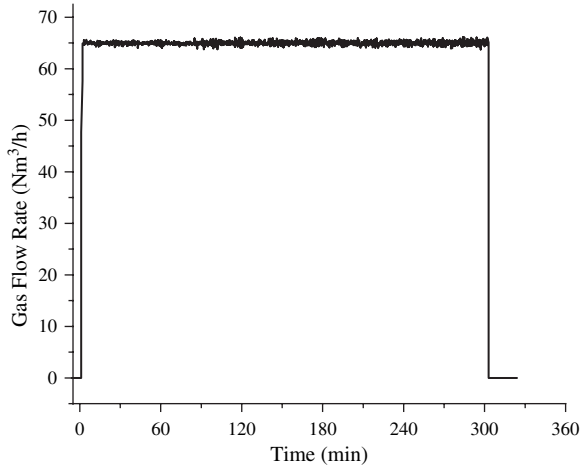


Fig. 4. The producer gas flow rate during a gasification run (wood chips with 9.5% moisture content and room-temperature air at ~23 °C).

controlled by the computer according to wood chips in the gasifier. Table III lists the material balance and energy balance analysis results. The consumption of wood chips was 26–30 kg/h with a syngas yield of 2.3–2.5 Nm^3/kg wood. The carbon conversion rate and hydrogen conversion rate were calculated based on Eqs. (2) and (3), respectively. The carbon conversion rate from wood to gaseous products (CO, CO_2 and CH_4) was above 92%. About 8% of carbon in wood chips was converted to other types of products, mainly char and tars. Compared to carbon conversion rate, the hydrogen content in wood chips was converted to gaseous products (H_2 and CH_4) at a low rate (67–75%). The syngas composition observed in this study was similar to the research performed at Auburn University.[32] Gautam et al. reported that based on the same downdraft gasification of pine wood chips, syngas composition was 44% N_2, 21.1% CO, 20.4% H_2, 12.2% CO_2, and 2.3% CH_4.

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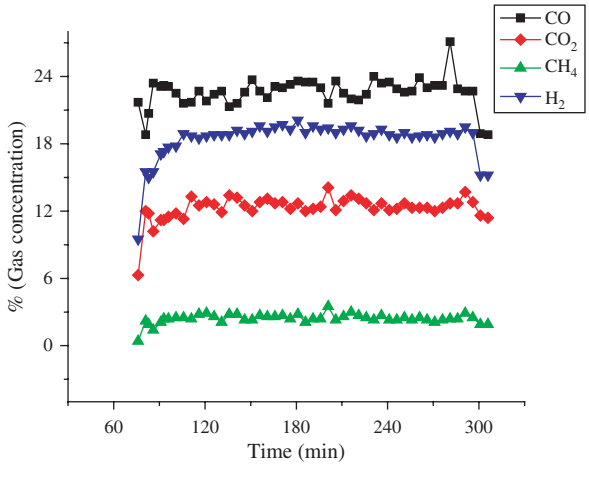


Fig. 5. Typical syngas composition monitored by a portable gas analyzer (wood chips with 9.5% moisture content and room-temperature air at ~23 °C).

Table II. A typical syngas volume composition by an Agilent 6890 GC.

	H_2	N_2	CO	CO_2	CH_4
Concentration (%)	17.4	48.0	20.8	10.3	1.7

The corresponding average LHV was reported to be 5.7 MJ/Nm^3.

$$\text{Carbon Conversion Rate}_{\text{wood to gas}} = \frac{\sum \text{Carbon Content}_{\text{gas}} * \text{Weight}_{\text{gas}}}{\text{Carbon Content}_{\text{wood chip}} * \text{Weight}_{\text{wood chip}}} \times 100\% \quad (2)$$

$$\text{gas} = \text{CO}, \text{CO}_2 \text{ and } \text{CH}_4$$

$$\text{Hydrogen Conversion Rate}_{\text{wood to gas}} = \frac{\sum \text{Hydrogen Content}_{\text{gas}} * \text{Weight}_{\text{gas}}}{\text{Hydrogen Content}_{\text{wood chip}} * \text{Weight}_{\text{wood chip}}} \times 100\% \quad (3)$$

$$\text{gas} = \text{H}_2 \text{ and } \text{CH}_4$$

3.2.4. Energy Balance

According to the heating value of wood chips and the producer gas, the energy conversion rate was calculated as 59–65% (from wood to syngas) based on Eq. (4) (Table III).

$$\text{Energy Conversion Rate} = \frac{\text{LHV}_{\text{syngas}} * \text{Volume}_{\text{syngas}}}{\text{LHV}_{\text{wood chip}} * \text{Weight}_{\text{wood chip}}} \times 100\% \quad (4)$$

The entrapped waste heat energy in the producer gas from the gasifier was calculated according to the gas composition, heat capacities and gas temperature when getting in the heat exchanger ($T_{\text{hex in}}$) (Eqs. (5) and (6)). The value of the heat capacity for each gas component was obtained from Ref. [31]. The waste heat energy was calculated from $T_{\text{hex in}}$ to 25 °C. Because the heat capacity of gas changed with temperature, its heat capacity-temperature relationship was linear-fitted into one or two linear equations for the calculations in Eqs. (5) and (6). The rest of the wood combustion energy was consumed by the gasifier for heating and gasification reactions (Eq. (7)). The waste heat energy rate was 10–12% according to our experiments (Table III). Our results were closed to the findings reported in prior studies about energy dissipation in a similar gasification system.[17]

$$\text{Waste Heat Energy} = \sum \int_{T_{\text{room}}}^{T_{\text{hex in}}} \text{Weight}_{\text{gas}} * C_{\text{p.gas}} dT \quad (5)$$

$T_{\text{hex in}}$, the temperature of gases when getting in the heat exchanger

T_{room}, room temperature at 25 °C

$C_{\text{p, gas}}$, the heat capacity of each gas component

gas = all components of the producer gas, i.e., N_2, H_2, CO, CO_2, CH_4 and H_2O.

$$\text{Waste Heat Energy Rate} = \frac{\sum \int_{T_{\text{room}}}^{T_{\text{hex in}}} \text{Weight}_{\text{gas}} * C_{\text{p.gas}} dT}{LHV_{\text{wood chip}} * \text{Weight}_{\text{wood chip}}} \times 100\% \quad (6)$$

$$\text{Energy consumed by gasifier (\%)} = 1 - \text{Energy Conversion Rate} - \text{Waste Heat Energy Rate} \quad (7)$$

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4. CONCLUSIONS

The gasification process with BioMax 25 downdraft gasifier was investigated using oak tree wood chips as the raw material and air as the oxidation gas. The temperatures in the combustion and reduction zones were stabilized between 700–900 °C. The consumption rate of wood chips was 26–30 kg/h while the flow rate of the producer gas at 65 Nm^3/h. The syngas was mainly composed of about 48% N_2, 21% CO, 18% H_2, 10% CO_2, and 2% CH_4 and its yield was about 2.5–2.7 kg/kg wood. The carbon and hydrogen conversion rates were above 92% (from wood to CO, CO_2 and CH_4) and 67–76% (from wood to H_2 and CH_4), respectively. Energy balance results showed that 59–65% of the wood heating value was converted to the producer gas while 10–12% of the wood heating value was dissipated by the producer gas.

Table III. Material balance and energy balance analysis of two gasification runs.

	Run 1	Run 2
Wood chip consumption rate (kg/h)	27.8	26.5
Moisture content of wood (%)	9.5	8.3
Syngas production rate (kg/h)	70.2	71.2
Sygngas yield (Nm^3/kg wood)	2.3	2.5
Biochar/ash yield (g/kg wood)	7.7	10.5
Carbon conversion rate (%)	92.1	98.9
Hydrogen conversion rate (%)	67.5	75.4
Syngas LHV (MJ/Nm^3)	5.1	5.3
Energy conversion rate (%)	59.5	65.2
Waste heat energy rate (%)	10.4	11.9
Energy consumed by gasifier (%)	30.1	22.9

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